Analysis of Total Installation Cost Versus Downlink Whole-Body SAR in Indoor Wireless Networks

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***Abstract*—Indoor exposure can be reduced by configuring the wireless network with more base stations with a lower transmit power. However, this causes significantly higher installation costs. In real-life deployments, a compromise could be sought between a low installation cost and a low exposure. This compromise is here numerically assessed and compared for different WiFi data rates, different path loss models, and different building layouts. Generally, whole-body Specific Absorption Rates (SARs) decrease exponentially as the allowed total cost increases. Buildings with line-of-sight conditions and lower throughput requirements allow deployments with a significantly lower installation cost (up to 79%) and exposure (up to 95%).**

***Index Terms*—SAR, exposure, WiFi, installation cost, electric-field strength, cabling**

I. Introduction

Recently, more attention is being paid the characterisation of radio-frequency (RF) fields [1]–[5] and the deployment of networks that cause a lower human exposure to RF fields. Generally, a lower and more homogeneous field strength can be obtained by adding more base stations and limiting their transmit power. Although this approach allows significantly reducing the exposure, it also leads to higher installation costs, due to the additional amount of cabling and working hours. In this paper, a network planner (WiCa Heuristic Indoor Propagation Prediction (WHIPP) tool [6]) will be used that combines a calculation of the electric-field strength and Specific Absorption Rate (SAR) due to the indoor base stations [7] with a calculation of the total total network installation cost (e.g., cabling, number of access points (APs),...) [8]. It will be determined how the exposure reduces as the total cost increases when more low-power APs are being used. It will be investigated how the required data rate, the path loss model, and the physical building layout influence the total cost, the exposure, and the relationship between both. For each of the proposed scenarios, two configurations with a different number of AP connectivity options will be compared. Although it can be expected that the whole-body SAR will reduce as more low-power APs are being deployed, this study is the first to numerically assess this relationship for different scenarios and configurations.

II. Methodology

A. Simulation tool

All simulations will be performed with the WHIPP tool, allowing an automatic network design with APs transmitting at a user-defined power [6]. In this paper, this Equivalent Isotropically Radiated Powers (EIRP) will be varied between 0 and 20 dBm. Once the automatic network design algorithm has determined the location and the EIRP of all APs, the WHIPP tool allows calculating e.g., a median electric-field strength E_{50} (V/m) observed in the building [9]. The median whole-body downlink SAR $\mathrm{SAR}_{50}^{\mathrm{wb}}$ is then calculated as follows:

$$\mathrm{SAR}_{50}^{\mathrm{wb}} = \mathrm{S}_{50} \cdot \mathrm{SAR}_{\mathrm{REF}}^{\mathrm{wb}}, \quad (1)$$

where S_{50} $[\mathrm{W/m^2}]$ is the median observed power density over the building floor and $\mathrm{SAR}_{\mathrm{REF}}^{\mathrm{wb}}$ [W/kg per $\mathrm{W/m^2}$] is the reference whole-body SAR (for 1 $\mathrm{W/m^2}$ of received power density). $\mathrm{SAR}_{\mathrm{REF}}^{\mathrm{wb}}$ equals 2.8 mW/kg per $\mathrm{W/m^2}$ for 2.4 GHz WiFi and is obtained from [10]. The power density S_{50} can be calculated using the median electric-field strength E_{50} (a worst-case duty cycle of 100 % is assumed):

$$\mathrm{S}_{50} = \frac{{\mathrm{E}_{50}}^2}{120 \cdot \pi}, \quad (2)$$

When the AP locations are known, the corresponding installation cost can be calculated based on the algorithm presented in [8]. Here, the cost of installing a WiFi network is calculated, based on the AP locations and the available ethernet connection points (ECPs) and power connection points (PCPs). In order to function properly, APs require a cabled connection to both an ECP and a PCP. The cost algorithm determines the cabling solution with the lowest cost, accounting for costs of ethernet and power cable, cable gutters, APs, and working hours (installing APs and cabling, drilling holes through walls). Table I lists the assumed cost calculation settings.

TABLE I
Cost calculation settings

	Unit price
Cable gutter	13.07 €/m
Ethernet cable	1.5 €/m
Power cable	4.55 €/m
AP	85.99 €
Working hours	67.50 €/h
Installing APs	2 APs/h
Drilling holes	5 holes/h
Installing cabling	15 m/h

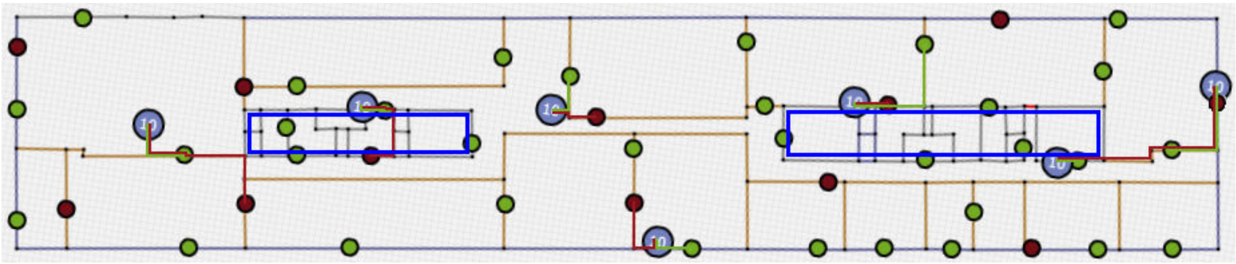

Fig. 1. Considered office building (90m x 17m) for reference scenario ($\mathrm{EIRP}_{\max} = 10$ dBm) with indication of APs (purple dots), ECPs (red dots) and PCPs (green dots) for the normal CP set, data cables (green lines), ethernet cables (red lines), and areas where no coverage is required (enclosed by blue rectangle).

B. Scenarios

In all scenarios, a shadowing margin of 7 dB and a fading margin of 5 dB are assumed for the coverage simulations. Each scenario is characterised by (1) a simulation environment, (2) a throughput requirement, and (3) a path loss model. Three scenarios will be defined and compared with a reference scenario.

- **Reference scenario**
  The reference scenario is based on the office building depicted in Fig. 1 (environment), corresponds with a throughput requirement of 37 Mbps (required received power of -68 dBm) in the rooms not enclosed by the blue rectangles (throughput), and assumes the IEEE TGn propagation model (path loss model) [11]. The rooms enclosed by the blue rectangles in Fig. 1 are kitchens, toilets, elevators, sheds,... and are assumed not to require wireless coverage. PCPs and ECPs are indicated in Fig. 1 with green and red dots respectively, and they are situated on walls.

The three additional scenarios will either vary the simulation environment, the throughput requirement, or the path loss model of the reference scenario.

- **Scenario 1: Simulation environment**
  In a first scenario, the physical environment of the reference scenario will be changed. Instead of the building depicted in Fig. 1, a new building is created, only composed of the 4 exterior walls in Fig. 1 (all inner walls and all CPs on the inner walls in Fig. 1 are removed). This corresponds to a building in which each receiver point will have a line-of-sight (LoS) connection with all APs in the room.
- **Scenario 2: Throughput requirement**
  In Scenario 2, the throughput requirement of the reference scenario is lowered from 37 Mbps to 18 Mbps. Consequently, less APs will be needed, corresponding to a lower installation cost and a lower exposure.
- **Scenario 3: Path loss model**
  In the third scenario, WHIPP's more advanced propagation model (sIDP [6]) is used, instead of the TGn model. This model has shown an excellent performance in the considered environment in [6].

For each of these scenarios, the relation between total installation cost and median SAR in the building will be assessed and compared for AP EIRPs varying between 0 and 20 dBm. This comparison will always be done for two different connection configurations. The first one consists of a normal set of ECPs (12 red dots) and PCPs (33 green dots) and is displayed in Fig. 1, whereas the second configuration consists of the reduced set with only 8 ECPs and 17 PCPs, as displayed in Fig. 2. The second configuration will in most of the cases require more cabling and more working hours to connect the APs to an ECP and a PCP and will thus correspond to a higher installation cost.
It should be noted that the AP positions as determined by the planning algorithm are chosen independently from the location of the CPs. Future research consists of an additional cost optimization where APs are preferably installed close to CPs.

III. Results

A. Reference scenario

As a function of the maximally allowed AP EIRP, Table II lists the number of APs required to provide a throughput of 37 Mbps, the resulting median electric-field strength E_{50} and median SAR $\mathrm{SAR}_{50}^{\mathrm{wb}}$ in the building, and the installation cost for the two types of connection point (CP) configurations: a normal CP configuration (Cost 1, see Fig. 1) and a CP configuration with fewer CPs (Cost 2, see Fig. 2).
Table II indicates that lower installation costs indeed correspond with higher exposures. When increasing the $\mathrm{EIRP}_{\max}$ from 0 to 20 dBm, the installation costs decrease from 5561 to 1075 € for the normal CP configuration (reduction by a factor 5.2) and from 6495 to 1075 € for the reduced CP set (reduction by a factor 6.0), but $\mathrm{SAR}_{50}^{\mathrm{wb}}$ increases from 10.3 nW/kg to 227.9 nW/kg (x 21.9). Fig. 1 shows the resulting network layout for the 7 APs with an EIRP of 10 dBm for the normal CP configuration (2415 €). This network can be considered as a trade-off solution: compared to the 20-dBm network, the $\mathrm{SAR}_{50}^{\mathrm{wb}}$ of the 10-dBm network still decreases significantly (from 227.9 nW/kg to 51.7 nW/kg (-77.3%)), and the installation cost increases more moderately (from 1075 to 2415 € (+125%, normal CP set) and to 2675 € (+149%, reduced CP set)). Fig. 3 shows $\mathrm{SAR}_{50}^{\mathrm{wb}}$ as a function of the

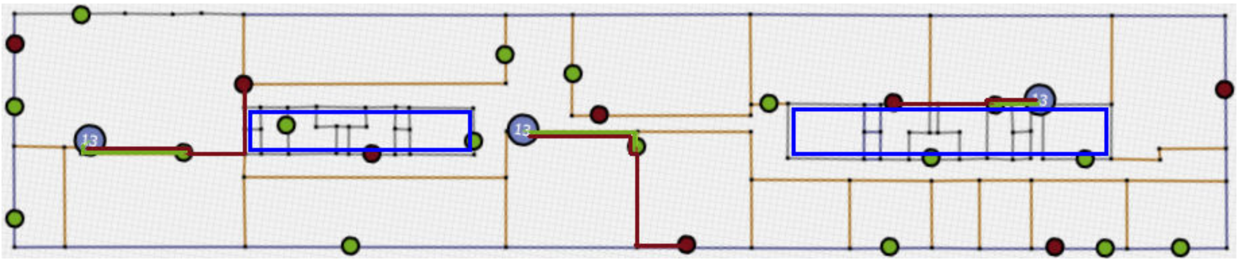

Fig. 2. Considered office building (90m x 17m) for Scenario 2 ($\mathrm{EIRP_{max}}$ = 13 dBm) with indication of APs (purple dots), ECPs (red dots) and PCPs (green dots) for the reduced CP set, data cables (green lines), ethernet cables (red lines), and areas where no coverage is required (enclosed by blue rectangle).

total installation cost for the two CP configurations (Scen Ref). It shows that the SAR decays in an exponential way as the cost increases. The reduced CP set leads to deployments that are 13% more expensive on average than the normal CP set, due to certain CPs of the normal CP set not being available in the reduced CP set.

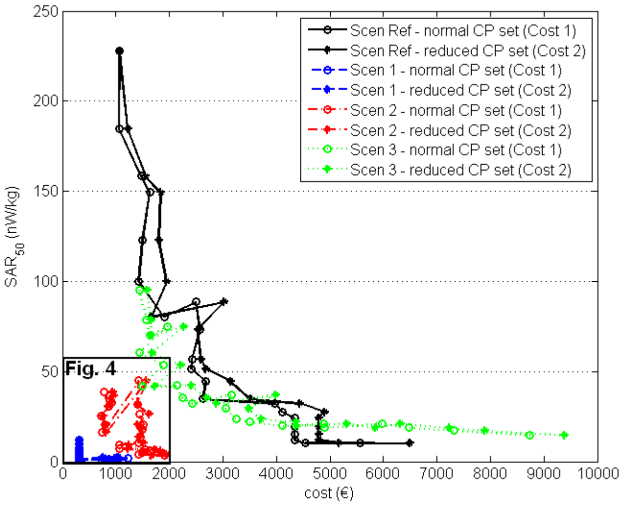

Fig. 3. Relation between total installation cost and $\mathrm{SAR}_{50}^{\mathrm{wb}}$ for the two CP configurations for all scenarios.

B. Scenario 1 - open building

In Scenario 1, all inner walls are removed so that every receiver point has a LoS connection with each AP. Table II shows that, logically, significantly fewer APs are needed to provide the coverage of 37 Mbps: 1 or 2 APs suffice to cover the entire building floor, even for low-power APs. Fig. 4 shows Fig. 3 in detail for Scenarios 1 and 2. For an EIRP of 9 dBm or more (encircled points in Fig. 4), 1 AP close to an exterior wall is placed. As the EIRP increases, the SAR increases, but the cost remains the same (see EIRP '9' to '20' in Fig. 4). For an EIRP between 4 and 8 dBm, the one AP needs to be located more centrally in the building. This causes a sudden increase of installation cost (from 312 to 1025 € for the normal CP set, see double arrow and '<9' in Fig. 4), since CPs are only present on the (exterior) walls. For an EIRP below 4 dBm, 2 APs are needed. These are again located close to the walls, resulting in a cost comparable to that of 1 central AP (1025€ for an EIRP between 4 and 8 dBm). Also the SAR remains comparable to that caused by 1 central AP. A very slight difference is noticed between the cost for the normal CP set and the reduced CP set. Differences arise when other CPs are used in the simulation with the reduced CP set. In this scenario, the reduced CP set appears to even result in a smaller cost in some cases. This scenario indicates that the total cost largely depends on a smart location of the APs close to the available CPs.

When comparing Scenario 1 with the reference scenario for the normal CP set, the average cost is 79% lower (604€ vs. 2899 €) and the average median SAR 95% lower (3.3 nW/kg vs. 72.6 nW/kg).

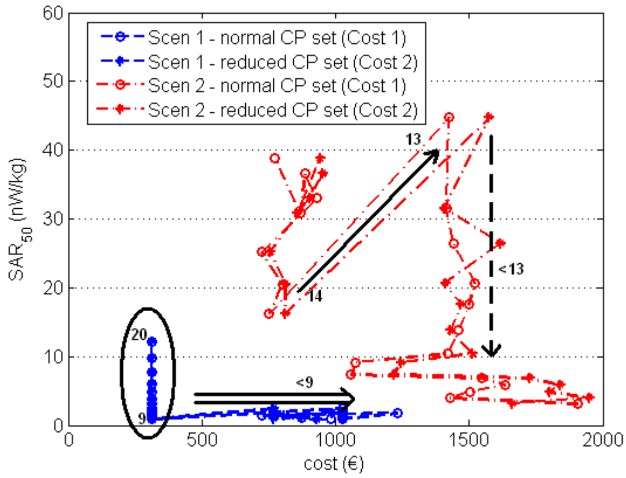

Fig. 4. Zoom-in of Fig. 3: relation between total installation cost and $\mathrm{SAR}_{50}^{\mathrm{wb}}$ for the two CP configurations for Scenarios 1 and 2.

C. Scenario 2 - lower throughput

In Scenario 2, the required throughput in the building is lowered to 18 Mbps. Table II shows that, depending on the EIRP, the building floor can be covered with 2 to 4 APs, of course lower than for the reference scenario. As the maximal EIRP decreases (from 20 to 0 dBm), there is a sudden SAR and cost increase between an EIRP of 14 and 13 dBm. This is caused by the additional AP that needs to be installed to achieve the required coverage. The arrow from '14' to '13' in Fig. 4 indeed shows that the (cost,SAR)-point moves

	Reference scenario (office building, 37 Mbps,TGn)					Scenario 1 (open building, 37 Mbps,TGn)				
$\mathrm{EIRP_{max}}$ (dBm)	#APs (-)	$\mathrm{E_{50}}$ (mV/m)	$\mathrm{SAR_{50}^{wb}}$ (nW/kg)	Cost 1 (€)	Cost 2 (€)	#APs (-)	$\mathrm{E_{50}}$ (mV/m)	$\mathrm{SAR_{50}^{wb}}$ (nW/kg)	Cost 1 (€)	Cost 2 (€)
0	14	37.32	10.3	5561	6495	2	10.95	0.9	984	928
1	12	37.34	10.4	4551	5179	2	12.29	1.1	874	874
2	11	40.37	12.1	4340	4791	2	13.79	1.4	725	808
3	11	45.29	15.2	4340	4791	2	15.47	1.8	1233	985
4	11	50.82	19.2	4340	4791	1	11.6	1.0	1025	769
5	11	57.02	24.2	4340	4791	1	13.01	1.3	1025	769
6	10	61.07	27.7	4116	4903	1	14.6	1.6	1025	769
7	10	66.05	32.4	3978	4439	1	16.38	2.0	1025	769
8	8	68.49	34.9	2634	3520	1	18.38	2.5	1025	769
9	8	77.51	44.6	2683	3138	1	11.4	1.0	312	312
10	7	83.45	51.7	2415	2675	1	12.8	1.2	312	312
11	6	87.53	56.9	2425	2598	1	14.36	1.5	312	312
12	6	99.45	73.5	2576	2530	1	16.11	1.9	312	312
13	4	109.25	88.7	2496	3026	1	18.08	2.4	312	312
14	4	104	80.4	1908	1662	1	20.28	3.1	312	312
15	4	115.95	99.9	1431	1948	1	22.76	3.8	312	312
16	4	128.58	122.9	1505	1803	1	25.54	4.8	312	312
17	4	141.8	149.4	1636	1840	1	28.65	6.1	312	312
18	4	146	158.4	1470	1551	1	32.15	7.7	312	312
19	3	157.75	184.9	1058	1220	1	36.08	9.7	312	312
20	3	175.14	227.9	1075	1075	1	40.48	12.2	312	312
AVERAGE	7.4	90.01	72.7	2899	3275	1.2	19.29	3.3	604	533

	Scenario 2 (office building, 18 Mbps, TGn)					Scenario 3 (office building, 37 Mbps, sIDP)				
$\mathrm{EIRP_{max}}$ (dBm)	#APs (-)	$\mathrm{E_{50}}$ (mV/m)	$\mathrm{SAR_{50}^{wb}}$ (nW/kg)	Cost 1 (€)	Cost 2 (€)	#APs (-)	$\mathrm{E_{50}}$ (mV/m)	$\mathrm{SAR_{50}^{wb}}$ (nW/kg)	Cost 1 (€)	Cost 2 (€)
0	4	20.75	3.2	1908	1662	25	44.71	14.9	8734	9384
1	4	23.13	4.0	1431	1948	19	48.28	17.3	7321	7899
2	4	25.65	4.9	1505	1803	18	50.34	18.8	6478	7230
3	4	28.29	5.9	1636	1840	15	53.46	21.2	5984	6319
4	4	30.48	6.9	1545	1726	13	50.11	18.7	4903	5849
5	3	31.47	7.4	1058	1220	13	53.52	21.3	4875	5315
6	3	34.94	9.1	1075	1246	10	51.78	19.9	4118	4366
7	3	37.46	10.4	1420	1514	9	54.38	22.0	3500	4358
8	3	43.12	13.8	1460	1431	8	56.35	23.6	3261	3717
9	3	48.65	17.6	1499	1470	8	63.01	29.5	3053	3484
10	3	52.84	20.7	1522	1411	7	70.69	37.1	3158	3994
11	3	59.7	26.5	1442	1619	6	66.17	32.5	2427	2880
12	3	65.18	31.6	1414	1405	5	69.19	35.6	2248	2705
13	3	77.64	44.8	1424	1575	5	75.32	42.2	2140	2405
14	2	46.84	16.3	751	814	4	75.04	41.8	1492	1726
15	2	52.56	20.5	803	813	4	85.02	53.7	1896	2218
16	2	58.22	25.2	725	756	4	90.17	60.4	1446	1677
17	2	66.59	33.0	930	903	4	100.37	74.9	1968	2269
18	2	70.19	36.6	885	953	3	97.19	70.2	1634	1660
19	2	64.47	30.9	867	856	3	102.88	78.7	1576	1666
20	2	72.27	38.8	773	942	3	113.3	95.4	1447	1582
AVERAGE	2.9	48.12	19.4	1242	1329	8.9	70.06	39.5	3508	3938

TABLE II
MAXIMAL EIRP ALLOWED, #APS REQUIRED, MEDIAN E AND SAR, AND CORRESPONDING INSTALLATION COST FOR A NORMAL CP SET (COST 1) AND A CP SET WITH FEWER CPS (COST 2) FOR ALL SCENARIOS.

away from the optimal values located towards the bottom left corner of the figures (low cost, low SAR). As the EIRP further decreases (dashed arrow and '<13' in Fig. 4), the SAR decreases, but the total installation cost shows no real trend: it varies according to the chosen AP locations (curve swings leftwards and rightwards along the dashed arrow in Fig. 4).

Due to the low number of deployed APs in Scenarios 1 and 2, the total cost largely depends on this choice of AP locations: deployments with a same number of APs can have largely different total costs due to cabling, drilling holes,... and no clear relation can be observed between SAR and cost. On average, the reduced CP set causes slightly higher costs than for the normal CP set (1329€ vs. 1242€).
When comparing Scenario 2 (low throughput) with the reference scenario (high throughput) for the normal CP set, the average cost is 57% lower (1242€ vs. 2899 €) and the average median SAR 75% lower (19.4 nW/kg vs. 72.6 nW/kg). Figs. 3 and 4 show that total cost and median SAR are higher for Scenario 2 than for Scenario 1.

D. Scenario 3 - advanced path loss model

In Scenario 3, the sIDP model described in [6] is used instead of the TGn model. Fig. 3 and Table II show that, due to the larger amount of required APs for this scenario (compared to Scenarios 1 and 2), the cost-SAR relation depends less on the specific AP locations and an exponential decay is again observed. Although the same trend as in the reference scenario is observed, differences are noticed in the tails of the curves. For low EIRPs (high costs), the sIDP model predicts larger amounts of required AP and thus also a larger cost (tail in the right bottom corner of Fig. 3): for the normal CP set, the average cost is 21% higher for Scenario 3 (3508€ vs. 2899 €, mainly due to the differences in low-EIRP deployments). For high EIRPs (low costs), the number of APs (and the cost) are similar, but the predicted SAR values are significantly higher in the reference scenario (upward tail in left top corner of Fig. 3): for the normal CP set, the average median SAR is 46% lower in Scenario 3 than for the reference scenario (39.5 nW/kg vs. 72.6 nW/kg, mainly due to the difference in high-EIRP deployments). These differences originate from differences between the path loss models: the sIDP model will for this environment e.g., predict lower path losses than the TGn model at larger distances from APs, causing a higher SAR predictions with the TGn model. Unlike like the TGn model, the sIDP model was validated in the considered environment [6] and it also takes into account the specific physical environment (wall types, wall penetration, diffraction,...). Therefore the sIDP model will yield more accurate network predictions, but requires more calculation time.
For Scenario 3, the reduced CP set leads to average costs that are 12% higher than for the normal CP set (3938€ vs. 3508€).

IV. Conclusions

In this paper, an analysis of the relation between the total installation cost of an indoor WiFi network and the corresponding whole-body SAR is performed. Generally, it can be stated that as the allowed installation cost increases, the whole-body SAR decreases exponentially. Three scenarios are defined and compared with a reference scenario. A deployment in an open building instead of in a regular office building leads to cost and SAR reductions of 79 and 95% respectively. Reducing the throughput requirement from 37 to 18 Mbps leads to cost and SAR reductions of 57 and 75%, respectively. Using a more advanced path loss model requires more calculation time, but yields more accurate results. Future work consists of optimizing the access point locations, based on the location of the ethernet and power connection points in the building.

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